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AUTOMATED MULTICHANNEL SYSTEM FOR IN-LINE MONITORING OF FLOAT-GLASS RIBBON THICKNESS IN THE HOT ZONE OF AN ANNEALING FURNACE

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The advances and 10 years of experience in operating automated multichannel systems for in-line monitoring of float-glass ribbon thickness, which led to serial production of such systems, are summarized.

The modern trends of increasing requirements on the quality of polished glass presume accurate and continual monitoring of various parameters, the most important of which is thickness. It is obvious that to minimize glass-mass losses continual monitoring of float-glass thickness must be performed in direct proximity to glass ribbon formation zone.

Triangulation thickness monitoring systems have been installed in a number of western enterprises [1]. When the triangulation method is used the thickness of the sample is calculated from the distance between beams of light reflected from the near and far surfaces of a glass ribbon. Even though the scheme presented is simple, it has a number of substantial drawbacks. The beams reflected from different surfaces propagate along different paths, and therefore the presence of turbulence (which is unavoidable in a furnace at high temperatures) results in the appearance of an uncontrollable error, which increases as the distance between the photodetector and the ribbon increases.

In addition, jittering of the ribbon and tapering over the thickness will likewise contribute errors, whose magnitude will increase as the distance from the sample increases. Thus, in order to perform accurate measurements the distance between the detector and the glass ribbon must be small; this distance is 15 – 20 mm in operating systems. Since the temperature in the measuring zone is high (over 500°C), the existing triangulation systems for performing measurements in the hot zone are equipped with a powerful water-cooling system and a system for blowing air on the heads to protect them from the atmosphere of the annealing furnace. The need to maintain the distance to the ribbon constant greatly complicates the optomechanical head positioning system. In addition, placing an expensive optical head close to the ribbon causes it to break when accidents occur on the line, such as strong buckling or detachment of the ribbon. As a result, the triangulation thickness measuring system is itself expensive, and it is expensive to service the system. The serviceability of such systems during the most critical transition periods where glass with one thickness is switched to glass with a different thickness engenders much criticism because of the large measurement errors, since it is precisely during such a transition that all parameters resulting in the errors of the triangulation system change rapidly and often exceed admissible values. In addition, existing triangulation systems have only one optical measuring head, which makes it impossible to obtain information about the behavior of the thickness profile of the glass ribbon continually.

In 1998 – 2000 the first prototypes of an automated system for technological monitoring of the thickness of a glass ribbon, based on the new principles of tandem low-coherence interferometry, were developed at the Institute of Microstructure Physics of the Russian Academy of Sciences (Nizhny Novgorod). The prototypes developed have passed industrial tests at the Bor Glass Works, where operation is successfully continuing.

Reformation of the Academy of Sciences made it necessary to separate research and applied work. Ultimately, the group developing the system created a startup company to manufacture systems for monitoring glass thickness. The name of this company is Scientific and Manufacturing Enterprise "Technological Electronic Optical Systems" (NPP "TEOS"). The modern variant of the system has been completely redesigned to meet European standards. Compared with the early variants [2], an entire series of new possibilities, such as a database and additional monitoring of the optical head, has been added to it.

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A fundamental feature of the method is the use of a wide-band light source with a short coherence length (approximately 20 μm), whose radiation passes successively through a pair of interferometers, often called tandem interferometers, hence the name — tandem low-coherence interferometry. In this configuration, interference can be observed at the exit of the entire system only if the differences of the arm lengths between the two interferometers differ by less than the coherence length of the source, i.e., the condition

$$|L_2 - L_1| = L_{coh},$$

where L_1 and L_2 are the differences of the arm lengths of the first and second interferometers, is satisfied.

Two waves will interfere: the first wave, which has traversed the short arm in the first interferometer and the long arm in the second one, and a second wave, which has traversed the long arm in the first interferometer and the short arm in the second one. In our case one of the interferometers is the glass ribbon being measured, which can be regarded as a Fabry – Perot interferometer, and the second interferometer — the measuring one — is placed in an optoelectronic measuring block and permits changing the difference of the arm lengths in a controlled manner. By adjusting this difference and determining the moment when the interference signal appears it is possible to determine the optical thickness of the object on which the measurements are being performed (the glass ribbon). A quite long optical fiber is used for optical coupling between the interferometers, making it possible to install a high-precision measuring interferometer under favorable conditions far from the measurement location.

A block diagram of the system developed is displayed in Fig. 1. The probe light from the output of the high precision measuring interferometer, placed inside the optoelectronic block, is fed into the fiber-optic lightguide, where it is separated into independent measuring channels. Propagating along a multifilament fiber optic cable, the probe light enters the optical heads, which focus it on the ribbon and also collect the light reflected from the ribbon back into the fiber. Next, the light returns into the optoelectronic block, where it enters photodetectors which are independent for each channel. Scanning the difference of the arm lengths of the measuring interferometer at the moment the optical thickness of the glass equals the difference of the arm lengths of the measuring interferometer at the output of each photodetector, there appears an interference signal, from which data on the optical thickness are extracted by digital processing with signal processors. As a result, independent measurements of the thickness are obtained in all channels immediately. The accuracy of the measurements and all channels is the same and is determined by the accuracy of the reading device, controlling the difference of the arm lengths of the measuring interferometer.

In principle, the number of measuring channels can be quite large. The limitations are due only to the power of the probe light which arrives in one channel and decreases as the number of channels. However, experience in operating the system at different plants showed that five channels placed across the glass ribbon are sufficient for engineers to reconstruct the transverse profile of the glass. An additional (monitoring) channel has been added in the latest version of the system to monitor the serviceability of the system, to perform calibration, and to enable the technical monitoring division to perform manual measurements. The corresponding optical head is located in the instrumentation rack.

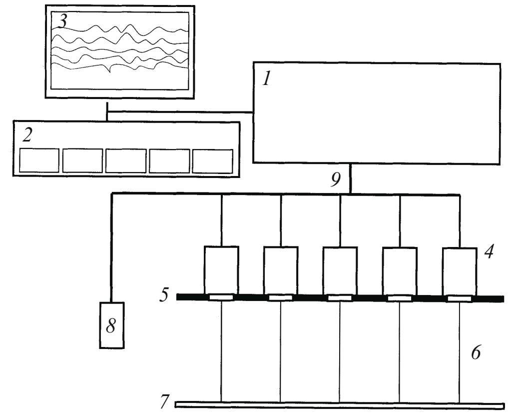

Fig. 1. Block diagram of the system: *1*) optoelectronic block; *2*) indicator; *3*) monitor for plotting the measurements; *4*) optical heads; *5*) crown of the annealing furnace; *6*) probe beam; *7*) glass ribbon; *8*) monitoring head; *9*) fiber-optic cable.

One of the main advantages of the design developed is the simplicity of the construction of the optical heads, which do not contain any moving or electronic components. In addition, the ribbon can be probed from a quite large distance (the distance to the glass ribbon is 1 – 1.5 m), which automatically solves the problem of protecting the system when accidents occur on the line. The most convenient and desirable location for securing the heads is the crown of the annealing furnace, which is as close as possible to the float-tank in order to increase the process control efficiency. As a result, the optical heads need no special cooling or servicing.

Another important advantage is that there are no errors when performing measurements of tapered glass as well as no noise associated with vibrations and turbulence of the furnace atmosphere. All this provides reliable, stable functioning of the system at the most important transitional stages of float-line operation, which substantially decreases the transition time from one glass ribbon thickness to another and substantially decreases production costs.

To compare the user properties of the triangulation system with those of the new system as clearly as possible, their main technical characteristics are summarized in Table 1.

A first-class diploma awarded “For high user properties of the product” at the international exhibition “The world of glass – 2006” (Moscow) confirmed the advantages of the new system. But the main confirmations of the advantages of our thickness meter are positive testimonials from users — the leading producers of float-glass in Russia (Bor, Klin,

Saratov, Salavat, and others), who, having worked with our system, preferred it to all other systems.

The measured quantity in the system is the optical thickness of the glass ribbon. It is defined as

$$D = nd,$$

where D is the optical thickness of the glass ribbon, n is the effective refractive index, and d is the geometric thickness of the glass ribbon.

The quantities n and d are temperature dependent. As a result, to determine the geometric thickness of cold glass the optical thickness measured by the system must be divided by the effective index of refraction taking account of the temperature in the measurement zone. In addition, this coefficient also depends on other parameters, for example, the composition of the charge. Nonetheless, for a properly working technological process, the spread of the indications which is associated with instability of the temperature and composition of the charge does not exceed 5 μm. Consequently, it is sufficient to perform the calibration procedure once during the setup operations.

Besides information on the running values of the ribbon thickness, it is helpful to know the "history of the thickness behavior," i.e., the change (fluctuation) of the thickness of the glass ribbon over a long period of the technological process. This helps engineers to understand better the subtleties of the processes occurring, monitor the quality of the work performed by the operators, and so on. To visualize the behavior of the glass thickness we developed a database which is installed in an industrial computer. The database permits reproducing, as clearly as possible, the course of the technological process over the previous year. For operating convenience, it also displays the admissible limits of the glass thickness provided by the government standard. In addition, engineers can set their own, in-plant, tolerance limits, above which the computer generates an appropriate warning.

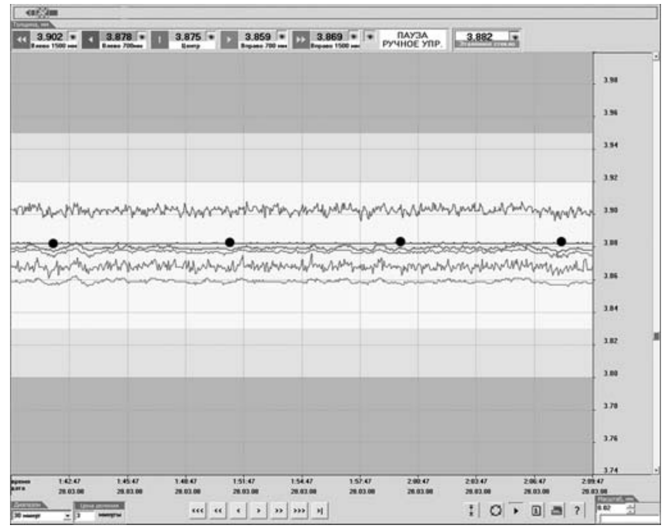

Fig. 2. "Gladkoe steklo" system for displaying the results of the measurements graphically.

An example of the use of the database is presented in Fig. 2, which displays the behavior of the ribbon in the production of glass with a thickness of 4 mm. Evidently, for a well-adjusted technological process the fluctuations of the glass ribbon thickness do not exceed 0.01 mm. The graphical indication of the tolerance limits enables the operators to monitor visually how well the thickness of the glass being produced satisfies the required limits. The black circles in the graph mark the plot of the measurements of the thickness by the monitoring head located above the sample. Evidently, this spread of the values does not exceed 0.001 mm.

However, smooth ribbons are encountered only extremely rarely. As a rule, the thickness of a ribbon has a wavy structure (Fig. 3*a*). Ordinarily, this is due to the beats of one or several edge-forming machines. Generally, experience shows that practically any operation on a float-line gives a

TABLE 1.

Technical characteristic	System	
	developed	triangulation
Number of measuring channels	5 – 7	1
Need for cooling	No	Double water cooling loop
Power consumption, W	300	7000
Assembly conditions	Assembly on the working line (without stopping the line) with minimum work on the line	Substantial additional work on the line (the working line must be stopped)
Distance from the heads to the glass ribbon, m	1 – 2	0.03
Presence of an additional channel for the quality control division	Yes	No
Sources of measurement errors	No	Tapering of the glass ribbon Turbulent flows of hot air Vibrations
Accuracy under working conditions, μm	1	10
Measurement time of the glass ribbon thickness profile, sec	2	1200 (20 min)

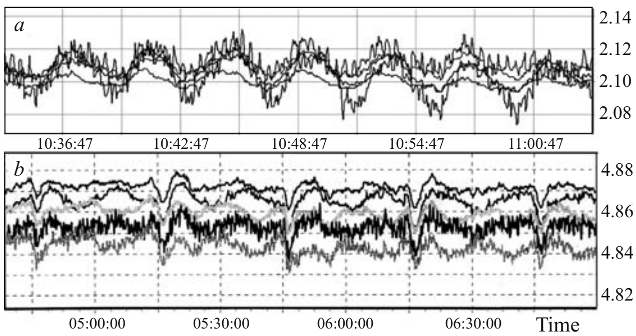

Fig. 3. Thickness fluctuations: *a*) wave-like fluctuations; *b*) fluctuations due to flame transfer.

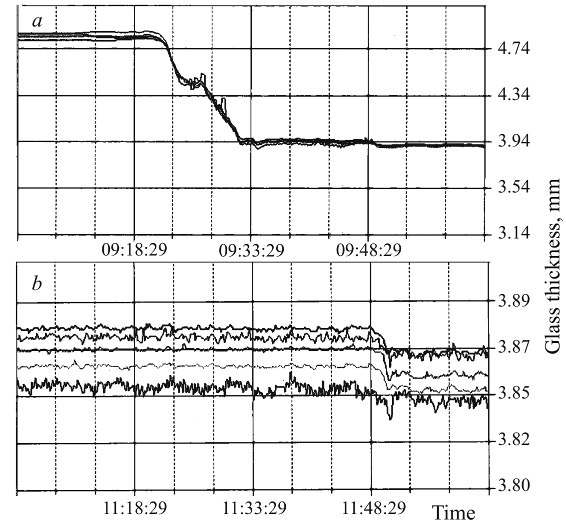

Fig. 4. Possibilities for controlling the technological process: *a*) transition times of glass ribbon from one thickness to another; *b*) decrease of thickness variations.

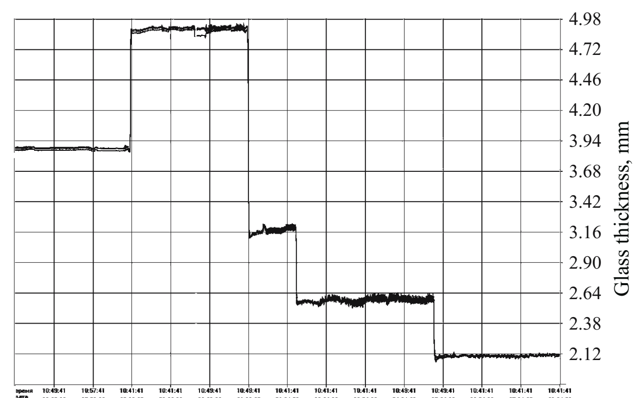

Fig. 5. Example of effective control of production — four transitions made during two weeks of operation.

response in the glass thickness. Thus, the periodic "troughs" in the thickness of a glass ribbon, as seen in Fig. 3*b*, were found to be due to the transfer of the flame in the melt furnace from one side to the other.

Since the measuring method on which the system is based is insensitive to tapering and jittering of the glass ribbon, the system makes it possible to monitor thickness, including during transitions when the glass is switched from one thickness to another during production. Such monitoring reduces the transfer time substantially. Figure 4*a* displays a plot of the transition of the system after two years of operation at the Bor Glass Works. Evidently, the transition is made in 10 min. Such a short transition time makes it possible to avoid unjustified losses of glass mass, greatly reduces the cost of production, and therefore substantially increases production flexibility, making it possible to produce glasses which are in greatest demand at any given time (Fig. 5).

Another important piece of information which the system provides is the thickness variation over the width of a ribbon. Figure 4*b* presents a very interesting moment when the operators decrease the thickness variations by means of the edge-forming machines. Considering the ever increasing requirements on thickness variation for automotive glass and for glasses used in glass packets, continual monitoring of the thickness can provide additional advantages in the competitive war with other glass producers, thanks to the higher quality of the product.

In conclusion, we shall indicate the possibilities which the new system opens up:

the transition time from one ribbon thickness to another is shorter;

the ribbon thickness remains the same when the productivity of the furnace changes;

the quality of the glass produced is higher because its thickness variations are smaller;

the consumption of glass mass is lower because the thickness is precisely adjusted to the lower tolerance limit;

rejects are avoided by timely signaling indicating that the glass thickness has exceeded prescribed limits;

the operators of the float-tank can operate in greater comfort;

the output of container glass increases;

production costs are much lower;

production flexibility is much higher.

As a result, the payback time of the system is 2 – 6 months, and if the system is started up together with the line, the payback time decreases to 1 month.

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